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An investigation into the performance of an Eddy Current Brake when varying the initial angular velocity of the aluminium disk being brought to rest

Session: May 2016

Candidate Name:

Candidate Number:

School:

IB Subject: Physics

Supervisor Name:

Page Count: 15

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1. Introduction

1.1. Research Question

How does the performance of an Eddy Current Brake vary with the initial angular velocity of the aluminium disk being brought to rest?

1.1.1. Approach to Research Question

From a young age trains, especially high-speed trains, have fascinated me. I often pondered upon the immense braking power that must be employed in order to bring the massive trains to a halt from such high speeds. I discovered that modern high-speed trains which travel at speeds of over $200km\ h^{-1}$ use Eddy Current Braking (ECB) systems in order to slow them down.[1] Eddy current brakes are highly effective in increasing the braking performance of high-speed trains.[2] This information sparked my interest and I began to wonder why ECB is not implemented in cars seeing as it would be more environmentally friendly. Having researched and explored opinions online I came to the conclusion that ECB is not efficient at low speeds therefore would not be effective in slowing down a car in everyday situations. I wondered to what extent this was true and if there would be any manner in which to overcome this deficiency. I therefore decided to research the effect of the initial angular velocity of an aluminium disk on the performance of ECB when bringing the disk to rest.

1.2. The Physics of Eddy Current Braking

1.2.1. Faraday's Law and Eddy Currents

Faraday's law states that when a conductor is introduced into an area of changing magnetic flux then an electromotive force (ε) is induced, and by virtue of Ohm's law, a current is also induced, known as an Eddy Current.[3]

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[1] "China Grips Technology To Brake World Fastest Train." *Arabia 2000* (2013): *Points of View Reference Center*. Web. 4 Oct. 2015.
[2] Alderas, Daniel, and Andrea, Demadonna. "Studying The Compatibility Of Eddy-Current Brakes." *Railway Gazette International* 171.8 (2015): 64. *Advanced Placement Source*. Web. 4 Oct. 2015.
[3] "Faraday'S Law Of Induction." *Encyclopædia Britannica* (2014): *Research Starters*. Web. 4 Oct. 2015.

Considering a spinning aluminium disk, when a magnet is introduced then any given point on the conducting disk experiences a changing magnetic flux as it passes the magnet, therefore there is a net current induced in the disk, in the form of Eddy Currents.

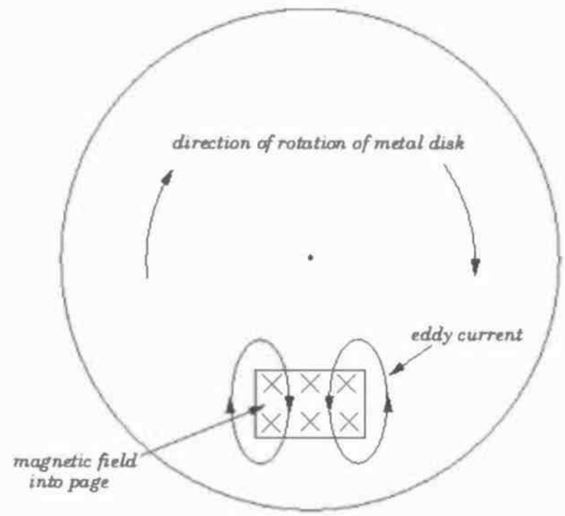

Figure 1. Eddy Currents induced in a spinning conducting disk[4]

1.2.2. Lenz's Law and Eddy Current Braking

Lenz's Law states that when a conductor is moving perpendicular to a magnetic field an electromotive force is induced in a direction that tends to oppose the motion of the conductor.[5] In other words, the current induced by the magnet in the aluminium disk will be in the direction that creates a magnetic field that opposes the motion of the disk. This results in the magnetic field of the magnet and the magnetic field of the Eddy Currents opposing each other, therefore creating a retarding force that slows the disk down.

A greater change in magnetic flux will induce a higher current; therefore the force of the opposing magnetic field induced will be stronger as will the retarding force. The change in magnetic flux will be higher when the disk has a higher angular velocity therefore I hypothesise that the higher the initial angular velocity, the greater the angular deceleration of the disk or in other words the greater the performance of the Eddy Current Brake.

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[4] Fitzpatrick, Richard. "Eddy Currents." *Eddy Currents*. Texas.edu. Web. 04 Oct. 2015.
[5] "Lenz's Law." *Columbia Electronic Encyclopedia, 6Th Edition* (2015): 1. *History Reference Center*.

1.2.3. Braking Performance

The braking performance is a measure of the brake's ability in bringing the disk to rest. The breaking performance can be expressed in terms of a force, in this case the resistive torque. Torque is proportional to angular deceleration by Newton's Second Law of rotation, $\tau = I\alpha$,[6] and therefore a higher angular deceleration means greater torque, and subsequently, a greater breaking performance.

2. The Investigation

2.1. Plan

The aim of the investigation is to verify my hypothesis that the higher the initial angular velocity, the greater the performance of the Eddy Current Brake. Furthermore I will investigate the nature of the proportionality between these two variables.

An apparatus will be constructed in which an aluminium disk is attached to a low friction bicycle hub; this will be suspended by two wooden blocks (from an old bookshelf) attached to a base made of wood. The base will have a hole cut directly underneath the bicycle hub, this will allow for a mass attached to a rope that is wound around the bicycle hub to drop through from a constant height, which will in turn make the aluminium disk spin. A magnet attached to a block of wood will be introduced next to the spinning disk through a small hole cut in one of the wooden supports, and will be at a constant distance from the disk. Changing the magnitude of the mass used will enable variation in the initial angular velocity of the disk, which will be able to be calculate. The process will also be filmed so that the time taken for the disk to be brought to rest can be accurately measured. Combining these two will allow me to calculate the angular deceleration of the disk, being a measure of its performance.

2.1.1. Variables

Independent:

- Mass (Initial Angular Velocity)

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[6] *IB Physics Data Booklet*

Dependent:

- Time taken to brake (Angular Deceleration)

Control:

Control Variable	**Why should it be controlled?**	**How will it be controlled?**
Height from which the mass is released	So that h is constant in the Potential Energy gained, therefore facilitating the calculation	Release the mass from a constant height in relation to the setup (95.1 ±0.05*cm*)
String used	So that the ability to turn the disk is constant	Use the same string
Length of string wound around axel	So that the mass is allowed to reach the floor while still turning the disk and so that the ability to turn the disk is constant	Use the same string
Distance of the Magnet from the disk	So that the magnetic flux is only affected by the speed of the disk and not the position of the magnet	By introducing the magnet to the disk using a hole in the wood that stops it at a constant distance (0.1-0.2 ±0.05*cm*, variation due to the bend in the aluminium disk)
The Strength of the Magnet	So that the magnetic flux is only affected by the speed of the disk and not the strength of the magnet	Use the same magnet (3 circular neodymium magnets attached together)
Width and diameter of Aluminium disk	So that the Eddy Currents induced aren't affected by a change in width or diameter	Use the same disk (0.080 ±0.005*cm* in width and 29.70±0.05*cm* in diameter)

2.2. Method

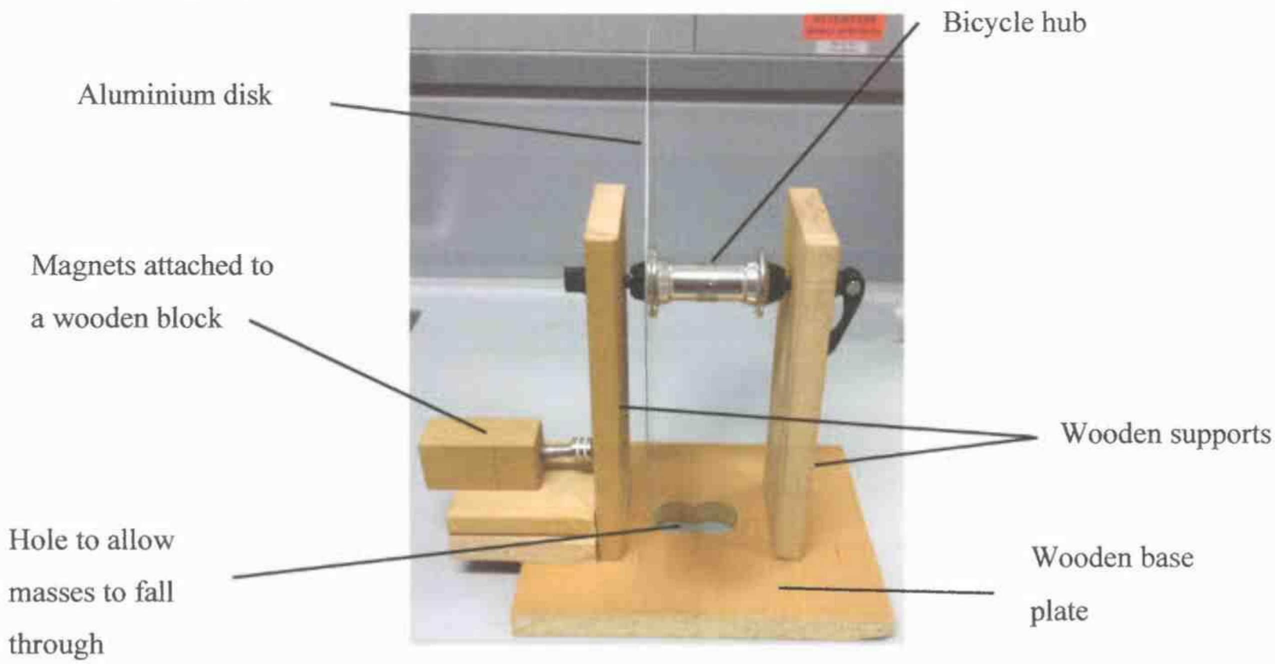


Diagram 1. Side view of Apparatus

Diagram 2. Front view of Apparatus

Table 1. Apparatus

Measurements	Value
Mass of disk and hub	297.77*g*
Height from which the masses are released	95.10*cm*
Diameter of hub (point around which the rope is wrapped)	2.490*cm*
Diameter of disk	29.70*cm*
Width of disk	0.10-0.20*cm*
Average actual weight of 100g mass	99.3*g*

Method:

1. Set up the equipment as in Diagram 1 and Diagram 2, using a disk of diameter close to 30*cm*, measure with a meter ruler and record (Refer to Table 1. for the measurements of the apparatus used in the experiment), also measure the diameter of the hub with a Vernier Caliper
2. Place the apparatus between two tables such that the bottom of the base plate is approximately 1.20*m* off the floor
3. Draw 4 red dots with a felt pen uniformly around the exterior of the aluminium disk
4. Set up a camera so that the red dots on the disk are visible, and mark the position of the camera so that it can be kept constant
5. Wrap a rope that has a knot at one end [7], uniformly and tightly around the bicycle hub, beginning at the side furthest from where the magnet will be introduced so that the knot hangs below the hub [8]
6. Hook a 200*g* mass to the knot and ensure constant starting height by rotating the hub until the top of the hook is level with the top of the base plate of wood [9], place books on the floor underneath the mass for safety, and such that the height between the books and the bottom of the mass at the starting height is as close to 1*m* as possible (measure with a meter ruler and record to keep constant), this is height h
7. Begin filming
8. Release the mass

[7 8 9] See Appendix

9. When the mass hits the floor, push the magnets (3 spherical neodymium super magnets) attached to the wooden block into position as swiftly as possible and with enough force that an audible click of the wood connecting with the magnets and the wood supporting the hub occurs
10. Hold the magnets in position until 2 seconds after the disk has come to rest
11. Stop Filming
12. Repeat steps 5-11 two more times
13. Repeat steps 5-12 replacing the 200g with 400*g*, 600*g*, 800*g*, 1000*g*, and 1200*g* masses

2.3. Raw Results

The time taken to brake was measured in the application Final Cut Pro. The *click* sound that was indicated in the method was taken as the start of the time to brake, and could be seen on the application as a spike in the audio

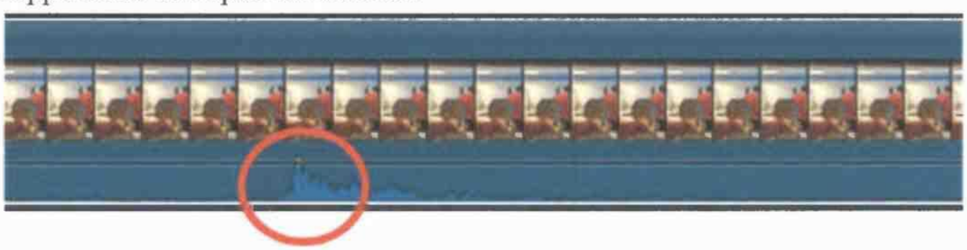


Figure 2. Spike in Audio from click

The end of the time to brake was indicated by the red dots drawn on the aluminium disk coming to a halt.

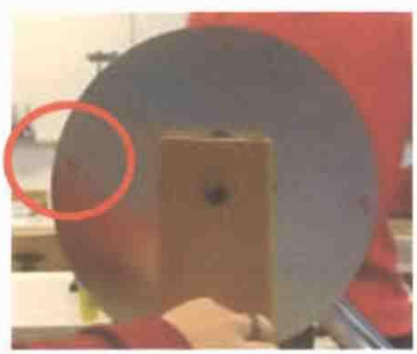


Figure 3. Red dots on disk

The times in the application were given in terms of seconds and a frame count of up to 30 per second. It was necessary to convert the frames into seconds by dividing the number of frames per trial by 30; the initial time was then subtracted from the final time to give a value for the time taken to brake.

Table 2. Variation of Time taken to brake with Mass

Mass *g*	Trial	Time to brake *s*	Average time to brake *s*
198.6	1	3.23	
	2	3.20	
	3	3.44	3.29
397.2	1	3.80	
	2	3.64	
	3	4.23	3.89
595.8	1	3.66	
	2	3.83	
	3	3.44	3.64
794.5	1	3.43	
	2	4.00	
	3	3.77	3.73
993.1	1	4.14	
	2	3.83	
	3	3.97	3.98
1191.7	1	3.56	
	2	3.70	
	3	3.87	3.71

As we can see from the table above, as the mass increases, the time taken for the Eddy Current Brake to bring the spinning disk to rest shows no significant variation, appearing to stay fairly constant. We can therefore deduce that as the mass increases, the angular deceleration also increases, seeing as it takes the same amount of time to bring the disk to rest from a high and a low initial angular velocity.

2.4. Processing the Results

2.4.1. Analysis of Raw Results: Deriving the Initial Angular Velocity

The Potential Energy of the mass at height h, $PE = mgh$, is equal to the sum of the kinetic energy gained by the falling mass and the spinning disk.

If the disk is spinning with angular velocity ω its rotational kinetic energy is

$$KE_{rot} = \frac{I\omega^2}{2}$$ [10]

For a disk of mass M and radius, R the moment of inertia;

$$I = \frac{MR^2}{2}$$ [11]

The angular speed of a disk is related to the tangential velocity, V of its outer edge;

$$\omega = \frac{V}{R}$$ [12]

Combining these equations;

$$KE_{rot} = \frac{MV^2}{4}$$

The kinetic energy of a falling mass m with velocity v is;

$$KE_{mass} = \frac{mv^2}{2}$$ [13]

Therefore the conservation of energy equation for the whole system is;

$$mgh = \frac{MV^2}{4} + \frac{mv^2}{2}$$

However seeing as the disk and the mass are connected by a rope which is wrapped around the inner bicycle hub of radius r, then the velocity of the outer edge of the disk is linked to the tangential velocity of the edge of the hub, v;

$$\frac{v}{r} = \frac{V}{R}$$

[10 11 12 13] *IB Physics Data Booklet*

Therefore

$$v = \frac{Vr}{R}$$

Since this is the same as the velocity of the falling mass, we can substitute into the conservation of energy equation;

$$mgh = \frac{MV^2}{4} + \frac{mV^2r^2}{2R^2} = V^2\left(\frac{M}{4} + \frac{mr^2}{2R^2}\right)$$

Rearranging:

$$V^2 = \frac{mgh}{\frac{M}{4} + \frac{mr^2}{2R^2}}$$

$$V = \sqrt{\frac{mgh}{\frac{M}{4} + \frac{mr^2}{2R^2}}}$$

V being the Tangential Velocity of the outer edge of the aluminium disk.

From this we can calculate the Initial Angular Velocity ω:

$$\omega = \frac{V}{r}$$ [14]

Seeing as we have the time taken for the disk to come to rest, we can therefore calculate the angular deceleration

2.4.2. Processed Results

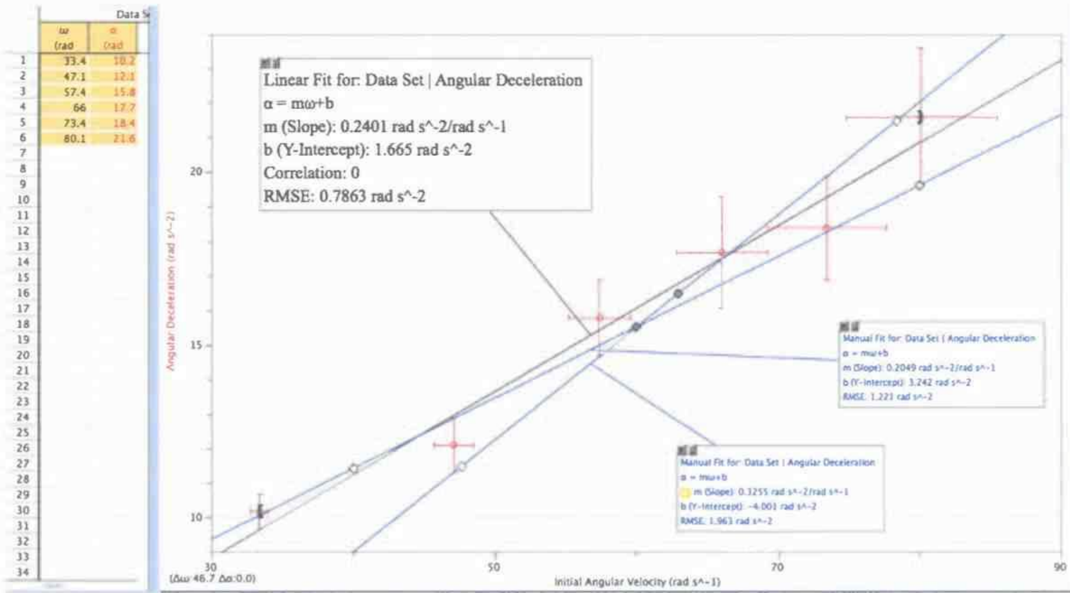
Table 2. Effect of Initial Angular Velocity on Angular Deceleration

Initial Angular Velocity *rad s⁻¹*	Error ±*rad s⁻¹*	Average Angular deceleration *rad s⁻²*	Error ±*rad s⁻²*
33.4	0.6	10.2	0.5
47.1	1.2	12.1	0.8
57.4	2.0	15.8	1.0
66.0	2.8	17.7	1.5
73.4	3.7	18.4	1.4
80.1	4.7	21.6	1.8

[14] *IB Physics Data Booklet*

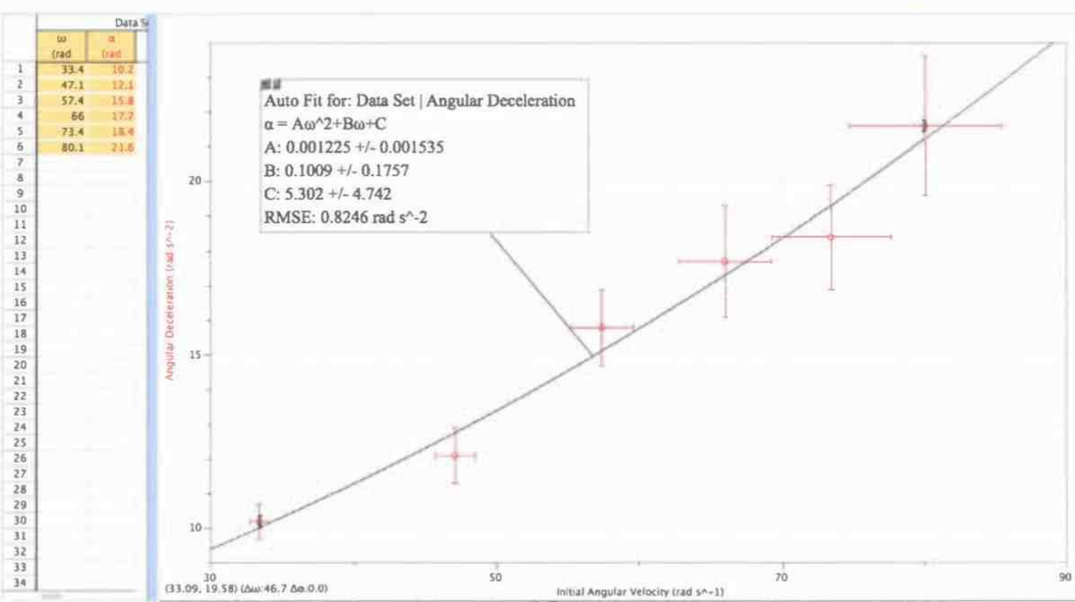
2.5. Analysis of Processed Results

Graph 1. Effect of Initial Angular Velocity on Angular Deceleration



As the Initial Angular Velocity increases, so does the Angular Deceleration. The graph presents us, within the boundaries of the random error bars, with a linear line of best fit of equation, $\alpha = 0.24\omega + 1.67$ and max min gradients that cover the origin. This indicates that there is a direct proportionality between the Initial Angular Velocity and the Angular Deceleration of the Aluminium Disk.

Graph 2. Effect of Initial Angular Velocity on Angular Deceleration



I noted however that a Quadratic line of best fit of equation, $\alpha = 0.0.0012\omega^2 + 0.10\omega + 5.30$ also fits the results very nicely within the boundaries of the error bars. This still indicates that the Initial Angular Velocity and the Angular Deceleration are related, however it would mean that there is a much larger increase in braking performance at higher speeds.

Looking at the RMSE values for both of the line of best fits, 0.7863*rad* s^{-1} for the linear best fit, and 0.8246*rad* s^{-1} for the quadratic, there is not a large enough difference to conclude which is the more accurate line of best fit and therefore cannot fully deduce the mathematical nature of the relationship.

3. Conclusion

The results of my experiment confirmed my hypothesis, as the Initial Angular Velocity increases, so does the Angular Deceleration. It can therefore be said that the greater the Initial Angular Velocity, the greater the performance of the Eddy Current Brake, which proves that they are very useful for high speed trains, but are unfortunately less suitable for low speed vehicles such as cars. This is as a result of the increased strength of the induced Eddy Currents at higher speeds due to the increased change in magnetic flux, which therefore creates a greater opposing magnetic field that produces a larger retarding force and slows down the disk at a greater rate.

A relationship was observed between the Initial Angular Velocity and the Angular Deceleration. According to Graph 1 the relationship is directly proportional seeing as the origin lies between the max min gradients. However according to Graph 2 the relationship is quadratic. Since both graphs were consistent with the data, within the random errors, the nature of the proportionality cannot be concluded, and the mathematical nature of the relationship cannot be deduced.

The investigation could be taken further by varying other aspects of the ECB system in an attempt to find a configuration of the Eddy Current Brake that works at lower speeds, which would possibly allow for implementation in cars. The thickness of the aluminium disk could be varied; as the thickness increases the Eddy Currents induced might be of greater magnitude, therefore might create a stronger magnetic field that would slow the disk down faster. Stronger magnets would increase the magnetic flux therefore might also induce stronger Eddy Currents and stronger opposing magnetic fields which would decrease the speed of the disk at a greater rate.

4. Evaluation

The errors in the measurements of the apparatus and constants used are as such;

Table 3. Uncertainties of Measurements

Measurements	Value	Error	SI equivalent	SI equivalent error	% Error
Mass of disk and hub	297.77*g*	0.01*g*	0.29777*kg*	0.00001*kg*	0.00336
Height from which the masses are released	95.10*cm*	0.05*cm*	0.951*m*	0.0005*m*	0.05258
Diameter of hub (point around which the rope is wrapped)	2.490*cm*	0.005*cm*	0.0249*m*	0.00005*m*	0.20080
Diameter of disk	29.70*cm*	0.05*cm*	0.297*m*	0.0005*m*	0.16835
Average 100g mass actual weight	99.3*g*	3.6*g*	0.0993*kg*	0.0036*kg*	0.36251

When calculating the error on the time, the error on each frame was 0.033*s* (±1 frame); therefore the error for each value of time taken to brake (a difference of times) was 0.7*s* (±2 frames). The standard deviation from the mean was found for each average time taken to brake at different masses, this value was added in quadrature to the error for one reading of time taken to brake, to find an overall percentage error for the time taken to brake.

Table 4. Error on Time and Error Propagation

Mass *g*	Trial	Time to brake *s*	Average time to brake *s*	Standard deviation of the mean *s*	% Error on time	Calculation Steps					
						$V = \sqrt{\frac{mgh}{\frac{M}{4}+\frac{mr^2}{2R^2}}}$				$\omega = \frac{V}{r}$	$\alpha = \frac{\omega}{t}$
						mgh *J*	$\frac{M}{4}$ *kg*	$\frac{mr^2}{2R^2}$ *kg*	Tangential V ms^{-1}	Angular ω $rads^{-1}$	Angular α $rads^{-2}$
198.6	1	3.23									
	2	3.20									
	3	3.44	3.29	0.06	2.84	1.853	0.074	0.001	4.966	33.440	10.164
397.2	1	3.80				0.366	0.003	1.101	1.721	1.890	4.725
	2	3.64									
	3	4.23	3.89	0.14	4.11	3.706	0.074	0.001	6.990	47.073	12.101
595.8	1	3.66				0.366	0.003	1.101	2.722	2.890	7.002
	2	3.83									
	3	3.44	3.64	0.09	3.18	5.559	0.074	0.002	8.522	57.389	15.752
794.5	1	3.43				0.366	0.003	1.101	3.704	3.873	7.050
	2	4.00									
	3	3.77	3.73	0.14	4.08	7.412	0.074	0.003	9.796	65.967	17.670
993.1	1	4.14				0.366	0.003	1.101	4.669	4.837	8.915
	2	3.83									
	3	3.97	3.98	0.07	2.54	9.265	0.074	0.003	10.903	73.422	18.448
1191.7	1	3.56				0.366	0.003	1.101	5.616	5.785	8.329
	2	3.70									
	3	3.87	3.71	0.07	2.73	11.118	0.074	0.004	11.891	80.072	21.583
Error						0.366	0.003	1.101	6.547	6.715	9.445

In the calculation steps the percentage errors are added when multiplying values, and the absolute errors are added when adding values. The blue boxes underneath each calculation step indicate the error propagation for that step in the form of absolute errors.

The experiment was in many ways successful. I was able to prove my hypothesis, and to show that as the Initial Angular Velocity increased, so does the Angular Declaration.

Another success was that my construction of the apparatus, using the bicycle hub and aluminium disk, resulted in a smoothly run and well-executed experiment that provided some interesting data to analyse.

The method that I employed was also very successful, and the manner in which I processed the data, using technological applications, proved to be rather effective, consequently producing some engaging results.

The experiment however did have a number of limitations. The first being that at the end of the descent of the masses that cause the disk to turn, there was not a great enough length of rope wrapped around the bicycle hub to create a lot of friction and therefore did not guarantee that the final moments of the fall of the mass resulted in an increase the angular velocity of the disk. This could be improved by increasing the surface friction of the hub with sandpaper. [15]

Another limitation was the fact that the bicycle hub used was not perfectly frictionless which therefore had an effect on the time taken to brake, however the time taken for it to slow down without the Eddy Current Brake was observed to be insignificant when regarding the precision of the experiment and therefore was not taken into account. This could be improved by utilising more bicycle grease on the hub.

Thirdly the aluminium disk used was unfortunately not uniformly flat, therefore the distance that the magnet was from the disk was not constant and varied by $0.1cm$, which resulted in the brake not being as effective as it potentially could have been. This could be improved by taking more care when preparing the disk so as to maintain its proper shape.

The next limitation was the relatively limited range of the Initial Angular Velocity; a range of 33.4-80.1 $rad\ s^{-1}$ was used due to time constraints. This meant that it could not be seen if the ECB system was completely ineffective at very low speeds, or if it was extremely performant at very high speeds. This could be improved by using a wider range of masses, and therefore a wider range on Initial Angular Velocities.

One of the most significant limitations was that the random error was unfortunately too large to come to a conclusion regarding the nature of the mathematical relationship between the

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[15] See Appendix

Initial Angular Velocity and the Angular Deceleration. This is a large limitation seeing as the findings can therefore not be extrapolated, subsequently; the behaviour of ECB at much higher or much lower initial angular velocities cannot be deduced from the results.

The final limitation was present in the derivation. The derivation of the Initial Angular Velocity does not take into account the fact that the formula for the moment of inertia doesn't apply to the aluminium disk and bicycle hub seeing as the total mass in not evenly distributed throughout the system. In reality there was a much greater mass present in the centre of the system because the bicycle hub was much heavier, if this was taken into account, the actual moment of inertia of the hub and disk would be smaller seeing as the majority of the mass is in the centre. Consequently the calculated angular deceleration would be higher since inertia is in the denominator of the equation for tangential velocity. This would cause a systematic increase in all calculated results, but the relationship would remain the same.

The variation in the masses of the weights used is the main source of random error. The error was found by calculating the variation of the actual weights used; in other words the inaccuracy in the standard weights. This error could be reduced by instead of assuming constant mass and calculating the uncertainty on the mass after performing the experiment, the masses could be weighed before being used in the experiment so that a more precise measurement for the mass in each trial could be used in the calculation.

5. Bibliography

5.1. Articles

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5.4. Equations

IB Physics Data Booklet

6. Appendix

Figure 4. Rope with a knot tied at one end

Figure 5. Rope wrapped around bicycle hub

Figure 6. Height of mass before release

Figure 7. Point at which rope loses friction

Group 4: Individual candidate cover sheet (biology, chemistry and physics)

Arrival date: **20 April / 20 October**

Session: May 2016

School number:

School name:

- Complete this form in the working language of your school (English, French, Spanish).
- The form must be completed by the teacher and candidate.
- A completed copy should be retained by the school.

Subject: Physics

Level: HL

Candidate name:

Session number:

Candidate section:

To be completed by the candidate.

Title of the group 4 project: Future Science, Future Solutions

Write a reflective statement of about 50 words outlining your involvement in the group 4 project:

My Group 4 project was about Water, the group's aim was to create a device that simultaneously filtered water whilst creating energy. I, along with two peers from the group specifically looked at the aspect of generating energy using a Water Turbine, and investigated the power produced with varying flow rates. We then created a design that implemented both the filtering and the power generation.

Title of individual investigation: An investigation into the performance of an Eddy Current Brake when varying the initial angular velocity of the aluminium disk being brought to rest

Candidate declaration: I confirm that this investigation is my own work and is the final version. I have acknowledged each use of words or ideas of another person, whether written, oral or visual.

Candidate's signature:

Date: 24/02/2016